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IMPERFECT MAGNETOSPHERE-IONOSPHERE COUPLING AND DISCRETE AURORAS

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Recent theoretical developments on the formation of discrete auroras are reviewed to assess the progress of our understanding of discrete auroral phenomenon. In spite of the great complexity involved, a unified physical picture begins to emerge in which the roles of various auroral acceleration processes can be identified in the context of magnetosphere-ionosphere coupling. Potential drops for the formation of inverted V precipitations are supported predominantly by a combination of double layer and pitch-

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angle anisotropy processes. Additional electron energizations for the formation of thin auroral arcs are most likely due to filamentations of electrostatic ion cyclotron turbulence along the inverted V field lines. The discrete auroras can be understood as a manifestation of the imperfect coupling state of the magnetosphere-ionosphere interaction due to enhanced magnetospheric convection.

1. Introduction

The results of our research supported under the Air Force Contract F19628-79-C-0046 have been presented in three papers:

(a) Double-layer criterion on the altitude of the auroral acceleration region (Kan and Lee, 1980);

(b) Theory of imperfect magnetosphere-ionosphere coupling (Kan and Lee, 1980);

(c) Generation of Alfvén waves by deceleration of magnetospheric convection (Kan, Lee, Chiu and Longenecker, 1981).

The purpose of this report is to summarize these results in perspective with the recent progress in auroral research. To set the stage for our theoretical discussion, it is necessary to briefly summarize what has been learned from observations including auroral morphology, field-aligned currents, electric fields, particles and waves on auroral field lines.

Discrete auroras appear as bright curtain-like structures extending along geomagnetic field lines. The latitudinal width of discrete auroras ranges from ~100 m for active arcs to ~10 km for homogeneous arcs [Davis, 1978], and up to ~100 km for inverted V electron precipitation bands [Frank and Ackerson, 1971; Lin and Hoffman, 1979]. Several thin auroral arcs often appear closely packed in a region believed to coincide with the inverted V precipitation band.

Discrete auroras are associated with precipitating electron fluxes peaked at energies between ~1 to 10 keV. These peaked electron fluxes appear to have been accelerated along geomagnetic field lines by parallel electric fields [Evans, 1972]. Outside the bright auroral forms, the average energy of precipitating electrons is usually around a few 100 eV [Arnoldy, 1974]. Field-aligned current density associated with bright discrete auroras is $\sim 10^{-5}$ A/m^2 [Anderson and Vondrak, 1975] and decreases to $\sim 10^{-6}$ A/m^2 under quiet conditions [Iijima and Potemra, 1978].

Equipotential structures deduced from electric field measurements on auroral field lines can be characterized as "V-shaped" and "S-shaped" [Gurnett, 1972; Cattell et al., 1979] as shown in Figure 1. The scale lengths L_x and L_z represent the latitudinal (i.e., transverse) and the field-aligned dimensions of the equipotential structure. For an auroral arc, $\lambda_D \lesssim L_x \lesssim$

ρ_i; for an inverted V, $L_x >> \rho_i$, where λ_D is the Debye length and ρ_i is the ion gyroradius. Observations indicate that the potential drop along auroral field lines is often extended with $L_z >> \lambda_D$ [Mizera and Fennell, 1977; Sharp et al., 1979] rather than localized .
Particle observations [Meng, 1978; Hultqvist, 1979] revealed the existence of five particle species along auroral field lines. These are:

(1) Precipitating magnetospheric electrons;
(2) Background magnetospheric ions;
(3) Upstreaming ionospheric ions;
(4) Ionospheric electrons;
(5) Trapped electrons and backscattered electrons produced from precipitating electrons (due to interactions with neutrals and waves).

The trajectories of these five particle species along the auroral field lines are schematically shown in Figure 2.

Plasma waves observed on auroral field lines can be classified as electromagnetic emissions and electrostatic turbulence. Electromagnetic emissions include auroral hiss, saucers, ELF noise and auroral kilometric radiation [Gurnett, 1978; Benson and Calvert, 1979]. Intense electrostatic turbulence in the frequency range of ~10 Hz to ~10 kHz has been observed to correlate with field-aligned currents [Gurnett and Frank, 1977; Temerin, 1978; Kintner et al., 1979]. These electrostatic waves are likely due to current-driven instabilities [Kindel and Kennel, 1971].

In addition to the east-west aligned arcs along auroral oval, there is a distinct class of sun-aligned arcs in the polar cap [Burke et al., 1981]. The polar cap arcs are known to correlate with the northward interplanetary magnetic fields, and hence present a unique opportunity for studying the energy transfer processes from the solar wind to the magnetosphere and the ionosphere under relatively undisturbed conditions.

2. Origin of Potential Drops Along Auroral Field Lines

In this section we summarize recent developments pertaining to the cause of potential drops along auroral field lines. It has been shown that enhanced magnetospheric convections lead to enhanced field-aligned currents and that potential drops are required when the enhanced upward field-aligned current density exceeds the limit set by the atmospheric loss cone. These interrelated processes are integral parts of the magnetosphere-ionosphere coupling system. The coupling can be termed "perfect" if geomagnetic field lines are equipotential with $E_{\parallel} = 0$ and "imperfect" if some field lines are non-equipotential with $E_{\parallel} \neq 0$. In this connection, the formation of discrete auroras can be considered as a manifestation of the imperfect coupling state due to enhanced magnetospheric convections.

2.1 Perfect Coupling State ($E_{\parallel} = 0$)

The importance of the ionosphere in regulating the magnetosphere was first recognized by Axford and Hines [1961], Dungey [1961] and Cole [1961]. Under the assumption of $E_{\parallel} = 0$, the interactions between the magnetosphere and the ionosphere have been studied extensively during the last two decades [Karlson, 1963; Fejer, 1964; Block, 1966; Wolf, 1970; Vasyliunas, 1970, 1972; Jaggi and Wolf, 1973; Mal'tsev, 1974; Wolf, 1974; Volland, 1975; Yasuhara and Akasofu, 1977; Nisbet et al., 1978; Sato, 1978; Nopper and Carovillano, 1978, 1979; Kamide and Matsushita, 1979a and b; Gizler et al., 1979; Miura and Sato, 1980; Harel et al., 1980a and b; Spiro et al., 1980].

A comprehensive effort in modeling the large-scale (~400 km in latitudinal width) magnetosphere-ionosphere coupling is being carried out by the Rice group [Harel et al., 1980a and b; Spiro et al., 1980]. This coupling model takes into account the effects of ionospheric conductivity and field-aligned currents in regulating the convection in the inner magnetosphere, where the convective inertia force and the plasma pressure gradient force are both important. Simulation results obtained from the Rice model can provide quantitative information for understanding the region II field-aligned current [Iijima and Potemra, 1976], the injection pheonomenon at the synchronous orbit [Deforest and McIlwain, 1971] and the shielding process of the convection near the inner edge of the plasma sheet [Southwood and Wolf, 1978].

In addition to the large-scale magnetosphere-ionosphere coupling through the large-scale field-aligned current system [Iijima and Potemra, 1976], there are small-scale field-aligned current sheets [Cloutier et al., 1970] imbedded in the large-scale current region. The source mechanism for driving the large-scale current system can be undertood in terms of the magnetospheric convection and pressure distribution in the plasma sheet [Wolf, 1970; Vasyliunas, 1972, Boström, 1975; Rostoker and Boström, 1976; Sonnerup, 1980]. The mechanism for driving the small-scale field-aligned current sheets is not so clear at present — the source could be located either in the ionosphere or in the magnetosphere.

A possible ionospheric source for the small-scale current sheets was proposed by Sato [1978] and further studied by Miura and Sato [1980], according to whom a series of upward and downward current sheets can be produced by a feedback instability driven by the north-south ionospheric current. They found that the ionospheric current is unstable to electrostatic perturbation if the magnetosphere acts as an inductive load in the equivalent electrical circuit. The model is formulated from the linearized MHD equations under the assumptions that $E_{\parallel} = 0$ and that the waves are totally reflected from the equatorial plane in the magnetosphere. These limitations of the model should be removed to see whether or not the model is applicable to the formation of auroral arcs.

There are several possible magnetospheric sources for the small-scale current sheets. One has to do with the nonlinear ion acoustic and ion cyclotron waves driven by the large-scale field-aligned current [Chaturvedi, 1976; Myra and Liu, 1979; Temerin et al., 1979; Böhmer and Fornaca, 1979; Lee and Kan, 1981]. These nonlinear electrostatic waves are accompanied by intense perpendicular electric fields with wave length on the order of the ion gyroradius. These wave electric fields can drive pairs of small-scale upward and downward field-aligned current sheets closing through the ionospheric Pedersen current. It is also possible to generate field-aligned current sheets by the ion tearing instability in the plasma sheet as proposed by Goldstein and Schindler [1978].

2.2 Imperfect Coupling State ($E_\parallel \neq 0$)

Alfvén [1958] was the first to point out the importance of the parallel electric field on auroral field lines. Axford and Hines [1961] attributed the geomagnetic activity during disturbed periods to enhanced magnetospheric convection. The connection between magnetospheric convection and parallel electric fields has been studied by Coroniti and Kennel [1972], Boström [1974], Kan and Akasofu [1976], Lennartsson [1977], Goertz and Boswell [1979], Chiu et al. [1980], Lyons [1980] and Sonnerup [1980]. Recently Kan and Lee [1980c] formulated a theory of steady state imperfect magnetosphere-ionosphere coupling ($E_\parallel \neq 0$) in which the magnetosphere as well as the ionosphere is allowed to respond to the effects of the parallel electric field.

Perhaps the single most important fact behind the imperfect magnetosphere-ionosphere coupling is the limitation of the upward field-aligned current by the atmospheric loss cone. The presence of upward parallel electric fields is required to relax this current limitation. [Knight, 1973; Lyons et al., 1979; Fridman and Lemaire, 1980]. In other words, an upward parallel electric field is required whenever the upward field-aligned current density exceeds $\sim 10^{-6}$ A/m^2. On the basis of this requirement, the imperfect coupling can be understood as a consequence of an enhanced magnetospheric convection [Kan and Lee, 1980c]. The basic physical processes leading to the imperfect coupling are summarized in the flow chart shown in Figure 3. An enhanced magnetospheric convection ($\underset{\sim}{E}_m$) leads to an increase in the field-aligned current density ($J_\parallel$) feeding into the Pedersen current ($\underset{\sim}{I}_p$) in order to speed up ionospheric convection ($\underset{\sim}{E}_i$). If the resulting upward field-aligned current density exceeds a certain value, a parallel potential drop is required, enabling the magnetospheric electrons to carry the current by modifying the atmospheric loss cone. The current-carrying electrons are accelerated by the parallel potential and subsequently enhance the ionospheric conductivity (Σ_p) and reduce the ionospheric electric field. On the other hand, the enhanced field-aligned current leads to enhanced cross-field current in the magnetosphere ($\underset{\sim}{J}_\perp$) which increases the loading effect ($\underset{\sim}{J}_\perp \cdot \underset{\sim}{E}_m < 0$) on the magnetospheric convection. The above processes have been formulated within the framework of the MHD equations [Kan and Lee, 1980c]. They showed that the equipotential contours can be distorted into V-shaped structures centered on the convection reversal boundary, and S-shaped structures away from the reversal boundary, as illustrated schematically in Figure 4.

The latitudinal scale length for the imperfect magnetosphere-ionosphere coupling [Kan and Lee, 1980c] is determined by the Pedersen conductivity via the closure of field-aligned currents in the ionosphere [Chiu and Cornwall, 1980]. Under moderately disturbed conditions, the latitudinal scale length is ~50 to 100 km, and increases with increasing Pedersen conductivity. In view of this scale length, we conclude that the inverted-V precipitation is a direct consequence of the imperfect coupling state, in which $E_{\parallel}$ is supported by the auroral double layer process. Additional processes, possibly ion cyclotron turbulence or nonlinear ion cyclotron waves, are requried to generate fine structures ($L_x \lesssim \rho_i$) for the formation of thin auroral arcs inside the inverted V precipitation region.

3. Processes Supporting Parallel Electric Fields on Auroral Field Lines

Several elementary processes have been proposed in the literature to show that parallel electric fields can be supported in collisionless plasmas [Fälthammar, 1978]. These elementary processes include: (a) double layers, (b) electrostatic shocks, (c) differential pitch-angle anisotropy, (d) thermoelectric process, (e) anomalous resistivity, and (f) Alfvén waves. The main purpose of this section is to bring forth the concept that the formation of discrete auroras can be better understood in terms of a combination of elementary processes, rather than a single elementary process.

3.1 Elementary Processes Supporting Parallel Electric Fields

(a) Double-Layer Process. Double layer is an electrical discharge phenomenon first studied by Langmuir [1929]. A double layer is a potential structure self-consistently supported in a current-carrying plasma in which oppositely streaming electrons and ions are accelerated and extract energy from the double layer potential.

Energy is supplied to the double layer potential by an external electromotive force (emf) in a closed electrical circuit. The potential drop in an unmagnetized double layer is localized in a few Debye lengths. On the other hand, the scale length of a magnetized double layer may depend on the ion gyroradius, the converging field scale length or the turbulent dissipation scale length which can be much greater than the Debye length. The presence of trapped electrons on auroral field lines play an important role in providing charges needed to maintain quasi-charge-neutrality in the extended potential structures along field lines. Magnitude of the double layer potential depends primarily on the applied emf in the circuit.

Double layers have been studied theoretically by Block [1972], Knorr and Goertz [1974], Kan [1975], Swift [1975], Levine and Crawford [1980], Kan and Lee [1980a]; experimentally by Langmuir [1929], Torven and Babic [1975], Quon and Wong [1976], Levine et al. [1978], Coakley and Hershkowitz [1979], Iizuka et al. [1979], and Stenzel et al. [1981]; and numerically by Goertz and Joyce [1975], DeGroot et al. [1977], Joyce and Hubbard [1978], Hubbard and Joyce [1979], Singh and Thiemann [1980], Sato and Okuda [1980] and Wagner et al. [1980].

(b) Electrostatic Shock Process. Electrostatic shocks are potential structures self-consistently supported in a streaming plasma [Moiseev and Sagdeev, 1963; Kennel and Sagdeev, 1967; Montgomery and Joyce, 1969; Forslund and Shonk, 1970; Tidman and Krall, 1971; Sakanaka et al., 1971; Mason, 1972; Biskamp, 1973]. There are no electrical currents in these electrostatic shock models. As the plasma flows through the shock potential, incident ions are decelerated while incident electrons are accelerated. The electron flux and the ion flux are individually conserved through the shock transition. Energy in the shock potential is supplied by the streaming ions and taken up by the streaming electrons. Since the ion flux equals the electron flux, the net energy gain by the shock potential is zero. The potential jump in a laminar electrostatic shock is localized in a few Debye lengths. This constraint on the scale length can be relaxed in the turbulent electrostatic shocks [Biskamp, 1973]. Magnitude of the shock potential is bounded by the ion streaming energy.

It should be noted that there is widespread confusion in the auroral literature concerning the distinction between the double layer and the electrostatic shock. This confusion arose when the term "electrostatic shock" was first introduced into auroral research by Kan [1975] and Swift [1975]. It turns out that the model considered by Kan [1975] was a hybrid between the double layer and the shock, while the model considered by Swift was an oblique double layer. It will become clear in the next section that the electrostatic shock process can make only a secondary contribution to the acceleration of auroral electrons.

(c) Differential Pitch-Angle Anisotropy Process. Alfvén and Fälthammar [1963] pointed out the possibility of supporting parallel electric fields by differential pitch-angle anisotropy between electrons and ions in the absence of field-aligned currents. This mechanism was further developed by Persson [1963, 1966], Whipple [1977], Ponyavin et al. [1977], Chiu and Schulz [1978], Chiu and Cornwall [1980]. The converging magnetic field plays an important role in this process. The energy source for the potential in this model lies in the thermal energy associated with the anisotropy. The maximum potential difference generated by this process is bounded by the thermal energy of Maxwellian electrons or ions, whichever is smaller [Ponyavin et al., 1977]. This restriction can be relaxed under special conditions [Alfvén and Fälthammar, 1963]. The potential drop in this case is extended, and $L_z \gg \lambda_D$.

(d) Thermoelectric Potential Process. Hultqvist [1971, 1972] suggested the thermoelectric contact potential between hot magnetospheric plasma and cold ionospheric plasma as a possible source of the parallel electric field on geomagnetic field lines. This effect can make a contribution to downward-directed electric field due to the higher mobility of the hot magnetospheric electrons, and thus could lead to deceleration rather than acceleration of precipitating electrons.

(e) Anomalous Resistivity Process. Anomalous resistivity results from the scattering of current-carrying electrons by the fields of unstable waves in a collisionless plasma. Steady-state anomalous resistivity depends on the ability of the plasma to sustain the wave turbulence in the nonlinear regime. The existence of steady-state anomalous resistance due to current-driven instability along auroral field lines remains somewhat controversial [Palmadesso et al., 1974; Ionson et al., 1976; Papadopoulos, 1977; Hudson et al., 1978 and references therein]. The most likely candidate for producing anomalous resistivity on auroral field lines appears to be electrostatic ion cyclotron turbulence [Kindel and Kennel, 1971] observed near 1 R_E altitude [Kintner et al., 1979]. A high level ion cyclotron turbulence can be sustained only if the perpendicular ion heating by the instability can be balanced by a heat transfer cooling process. Laboratory experiments on ion cyclotron turbulence [Bohmer and Fornaca, 1979] showed that ion heating results in a low-density, warm core surrounded by a denser hot ion cloud. Therefore, a high level ion cyclotron turbulence can be sustained in a core of ion gyroradius scale. Thus, it is possible for an unstable field-aligned current to produce intense ion cyclotron turbulence in thin sheets of widths comparable to the ion gyroradius. This filamentation process can produce fine structures in an unstable field-aligned current region and lead to the formation of auroral arcs imbedded in the inverted V precipitation region.

(f) Alfvén Wave Process. Parallel electric fields associated with oblique Alfvén waves have been considered as a possible mechanism for accelerating auroral electrons by Fejer and Kan [1969], Hasegawa [1976], and Goertz and Boswell [1980]. This process may contribute to transient or periodic acceleration of electrons along filed lines. It should be noted that Mallinckrodt and Carlson [1978], Sato [1978], Miura and Sato [1980] and others have studied propagations of Alfvén waves without parallel electric fields on auroral field lines. Possible sources for generating Alfvén waves on auroral field lines will be discussed in a later section. Such parallel electric fields arise mainly due to finite Larmor radius corrections to the usual MHD Alfvén mode. These short wavelength ($k_\perp \rho_i \approx 1$) Alfvén waves are usually called kinetic Alfvén waves.

3.2 Distinction Between Double Layers and Electrostatic Shocks

As is evident in the literature, the double layer and electrostatic shock theoreis were developed as two independent entities until the term "electrostatic shock" was introduced into auroral research by Kan [1975] and Swift [1975]. The resulting confusion was further compounded by Hudson and Mozer [1978]. Goertz [1979] made an attempt to clarify the confusion.

Kan [1980] noted that the basic physical differences between the double layer and the electrostatic shock processes are: (i) the current $J_{\parallel} \neq 0$ in the double layer, while $J_{\parallel} = 0$ in the electrostatic shock; (ii) the immediate energy source for the double layer potential is electrical (through $J_{\parallel} \neq 0$), while for the electrostatic shock it is mechanical (through ion streaming energy); (iii) the streaming ions are accelerated in the double layer while they are decelerated as they flow through the electrostatic shock.

Figure 5 illustrates schematically the differences between the double layer and the electrostatic shock. The average velocities $\langle V_e \rangle$ and $\langle V_i \rangle$ are in opposite directions in the double layer while they are in the same direction in the electrostatic shock. The electron flux and ion flux are individually conserved, which leads to the conservation of current with $J_{\parallel} \neq 0$ in the double layer and $J_{\parallel} = 0$ in the electrostatic shock. The kinetic energy K_e gained by the electrons is positive in both the double layer and the electrostatic shock; the kinetic energy K_i gained by the ions is positive in the double layer and negative in the shock.

From the above discussion, it can be seen that the electrostatic shock has very little to do with the acceleration of auroral electrons since the precipitating electron flux is always much greater than the precipitating ion flux on discrete auroral field lines. The energy supplied to the potential by the electrostatic shock process is proportional to the precipitating ion flux which is only a small fraction of the energy extracted by the precipitating electron flux. Hence, the energy for the potential can be expected to be supplied predominantly by the electromotive force in the circuit as in the double layer process.

3.3 Auroral Acceleration Process

As discussed earlier, auroral observations indicate: (i) the presence of upward field-aligned currents on discrete auroral field lines, $J_{\parallel} \neq 0$; (ii) the presence of both hot magnetospheric plasma and cold ionospheric plasma; (iii) upstreaming ionospheric ions; (iv) trapped and backscattered electrons; and (v) an extended potential drop along field lines ($L_z >> \lambda_D$).

Comparison between the observed characteristics and the elementary processes (discussed in Section 2.1) suggests that the primary auroral acceleration process is a combination of the four elementary processes (a)-(d). Of these four processes, the double layer process and the differential pitch-angle anisotropy process are probably dominant in maintaining the potential drop along auroral field lines. The extended potential structure on auroral field lines ($L_z >> \lambda_D$) is certainly a characteristic of the pitch-angle anisotropy process. However, since upward field-aligned currents are always associated with discrete auroras and the potential drops (a few KV) are often much greater than the thermal energy of the magnetospheric electrons on auroral field lines (a few 100 eV), the double layer process appears to dominate over the pitch-angle anisotropy process at least when the precipitating electrons are more energetic (~5 to 10 keV). Moreover, the main energy source for the potential drop on auroral field lines is the electromotive force (emf) powered by the magneotspheric convection as discussed in Section 2. From the electrical circuit point of view, the potential drops along auroral field lines are maintained by the double layer process, regardless of the scale length of the potential structure. For these reasons, we suggest the term <u>auroral double layer</u> for the observed extended potential structures along auroral field lines.

Models developed in recent years for the auroral acceleration region are slowly converging toward the concept of the auroral double layer [e.g., Swift [1976; 1979], Chiu and Shulz [1978], Kan et al. [1979], Gile [1979], Chiu and Cornwall [1980], Kan and Lee [1980a; 1980b], Wagner et al. [1980]]. From these studies, it is found that the presence of trapped electrons and backscattered electrons is of fundamental importance in supporting the extended potential structure alng congerging auroral field lines.

This and other characteristics of the auroral double layer are reviewed in the monogrpah by Lee and Kan [1981].

At this point, it may be useful to comment on the difference among existing two-dimensional auroral double layer models. Swift [1976; 1979] presented a model with $L_x \sim 2\rho_i$ in a uniforma magnetic field. Since the backscattered and trapped electrons are not included in Swift's model, quasineutrality along field lines can only be maintained by the polarization drift of the upstreaming ionospheric ions. Due to this limitation, Swift [1979] noted that explicit solutions of his model have not yet been obtained. Kan et al. [1979] presented a model with $L_x \sim \lambda_D < \rho_i$ in a converging magnetic field. This model is developed for thin auroral arcs of a few 100 m [Maggs and Davis, 1968]. The upstreaming ions in this model are highly nonadiabatic. These ions oscillate back and forth across field lines while being accelerated upward by the parallel electric field. The highly nonadiabatic motions of these ions cannot be approximated by the polarization drift. For this reason, we choose to describe the number density of the upstreaming ions by treating them as unmagnetized. This could have underestimated the ion number density by a factor of $\sqrt{2}$. The quasineutrality along field lines is achieved by the backscattered and trapped electrons. This model has been further studied by Wagner et al. [1980] using a numerical simualtion technique. The formation of the V-potential double layer is indeed found to depend critically on the back-scattered and trapped electrons.

Chiu and Cornwall [1980] presented a model with $L_x >> \rho_i$ in which the polarization drift in unimportant. In this model, the scale length L_x is determined by the ionospheric conductivity through the closure of the large-scale field-aligned current. Again, the quasineutrality along field lines is maintained by the trapped and backscattered electrons in this model. Finally, it should be noted that Giles [1979] presented a model with $L_x \sim \lambda_D >> \rho_i$. This model is not applicable to the auroral problem due to the assumption of $\lambda_D >> \rho_i$ which cannot be satisfied on auroral field lines.

3.4 Summary

From the above discussion, it seems reasonable to conclude that the primary process for supporting quasi-static parallel electric fields on auroral field lines is the auroral double layer process, a combination of the four elementary processes (a)-(d) but dominated by the elementary double layer processes. Since the anomalous resistivity process (e) can operate in thin current sheets with thickness comparable to the ion gyroradius through filamentation of an unstable current by ion cyclotron turbulence [Böhmer and Fornaca, 1979], it may contribute to the potential drop in thin auroral arcs. The Alfvén wave process (f) may also contribute to the parallel electric fields on auroral field lines, but is unlikely to be a major factor for the acceleration of auroral electrons. An overall summary of this section in given in Table 1.

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TABLE (1) AURORAL ACCELERATION PROCESSES

Characteristics Processes	$J_\parallel$	Energy Source	Remarks
(a) double layer	$J_\parallel \neq 0$	electrical energy (emf)	Auroral double layer process = (a) + (b) + (c) + (d), biased toward (a) and (c).
(b) electrostatic shock	$J_\parallel = 0$	ion streaming energy (mechanical)	Quasi-static laminar potential structure
(c) pitch-angle anisotropy	$J_\parallel = 0$	thermal energy	$L_x \sim \lambda_D$ to $\gg \rho_i$, $L_z \gg \lambda_D$
(d) thermoelectric	$J_\parallel = 0$	thermal energy	potential drop along field line $\Psi >$ few kV
(e) anomalous resistivity	$J_\parallel \neq 0$	electron streaming energy	Turbulent potential structure $L_x \lesssim \rho_i$, $L_z \gg \lambda_D$
(f) Alfvén wave	$J_\parallel \neq 0$	wave energy	Transient or periodic potential $L_x \gtrsim \rho_i$, $L_z \gg \lambda_D$

References

Alfvén, H., and C.-G. Fälthammar, Cosmical Electrodynamics, Fundamental Principles, p. 162, Clarendon Press, Oxford, 1963.

Anderson, H.R., and R.R. Vondrak, Observations of Birkeland currents at auroral altitudes, Rev. Geophys. Space Phys., 13, 243, 1975.

Arnoldy, R.L., Auroral particle precipitation and Birkeland currents, Rev. Geophys. Space Phys., 12, 217, 1974.

Axford, W.I., and C.O. Hines, A unifying theory of high-latitude geophysical phenomena and geomagnetic storms, Can. J. Phys., 39, 1433, 1961.

Benson, R.F., and W. Calvert, ISIS 1 observations at the source of auroral kilometric radiation, Geophys. Res. Lett., 6, 479, 1979.

Block, L.P., On the distribution of electric fields in the magnetosphere, J. Geophys. Res., 71, 855, 1966.

Block, L.P., Potential double layers in the ionosphere, Cosm. Electrodyn., 3, 349, 1972.

Böhmer, H., and S. Fornaca, Experiments on nonlinear effects of strong ion cyclotron wave turbulence, J. Geophys. Res., 84, 5234, 1979.

Boström, R., Ionosphere-magnetosphere coupling in Magnetospheric Physics, ed. by B.M. McCormac, D. Reidel Publ. Co., Dordrecht-Holland, 1974.

Cattell, C.A., M.K. Hudson, R.L. Lysak, M. Temerin, R.B. Torbert, and F.S. Mozer, Measurements of mechanisms associated with low altitude auroral particle acceleration by the S3-3 satellite, EOS, AGU 60, 18, 346, 1979.

Chaturvedi, P.K., Finite amplitude electrostatic ion cyclotron modes, Phys. Fluids, 19, 1064, 1976.

Chiu, Y.T., and J.M. Cornwall, Electrostatic model of a quiet auroral arc, J. Geophys. Res., 85, 543, 1980.

Chiu, Y.T., J.M. Cornwall, and M. Schulz, Auroral magnetosphere-ionosphere coupling: A brief topical review, Solar-Terrestrial Predictions Proceedings, ed. R.F. Donnelly, Vol. 2, p. 494, NOAA, Boulder, Co., 1980.

Cloutier, P.A., H.R. Anderson, R.J. Park, R.R. Vondrak, R.J. Spiger, and B.R. Sandel, Detection of geomagnetically aligned currents associated with an auroral arc, J. Geophys. Res., 75, 2595, 1970.

Coakley, P., and N. Hershkowitz, Laboratory double layer, Phys. Fluids, 22, 1171, 1979.
Cole, K.D., On solar wind generation of polar geomagnetic disturbance, Geophys. J., 6, 103, 1961.
Davis, T.N., Observed characteristics of auroral forms, Space Sci. Rev., 12, 77, 1978.
Deforest, S.E., and C.E. McIlwain, Plasma clouds in the magnetosphere, J. Geophys. Res., 76, 3587, 1971.
DeGroot, J.S., C. Barnes, and A.E. Walstead, Localized structures and anomalous dc resistivity, Phys. Rev. Lett., 38, 1283, 1977.
Dungey, J.W., Interplanetary magnetic field and the auroral zones, Phys. Rev. Lett., 6, 47, 1961.
Evans, J.W., Auroral particles and fields, Ann. Geophys., 28, 639, 1972.
Fälthammar, C.-G., Generation mechanisms for magnetic-field-aligned electric fields in the magnetosphere, J. Geomag. Geoelectr., 30, 419, 1978.
Fejer, J.A., Theory of geomagnetic daily disturbance variations, J. Geophys. Res., 69, 123, 1964.
Fejer, J.A., and J.R. Kan, A guiding center Vlasov equation and its application to Alfvén waves, J. Plasma Phys., 3, 331, 1969.
Forslund, D.W., and C.R. Shank, Formation and structure of electrostatic collisionless shocks, Phys. Rev. Lett., 25, 1699, 1970.
Frank, L.A., and K.L. Ackerson, Observations of charged particle precipitation into the auroral zone, J. Geophys. Res., 76, 3612, 1971.
Fridman, M., and J. Lemaire, Relationship between auroral electron fluxes and field-aligned electric potential difference, J. Geophys. Res., 85, 664, 1980.
Giles, M.J., Approximate equipotentials for electrostatic V-shocks, Planet. Space Sci., 27, 1311, 1979.
Gizler, V.A., V.S. Semenov, and O.A. Troshichev, Electric fields and currents in the ionosphere generated by field-aligned currents observed by Triad, Planet. Space Sci., 27, 223, 1979.
Goertz, C.K., and G. Joyce, Numerical simulation of the plasma double layer, Astrophys. Space Sci., 32, 165, 1975.
Goertz, C.K., and R.W. Boswell, Magnetosphere-ionosphere coupling, J. Geophys. Res., 84, 7239, 1979.

Goldstein, H., and K. Schindler, On the role of the ionosphere in substorms: Generation of field-aligned currents, J. Geophys. Res., 83, 2574, 1974.

Gurnett, D.A., Electric field and plasma observations in the magnetosphere, in Critical Problems of Magnetospheric Physics, ed. by E.R. Dyer, 123, Nat. Acad. Sci., Washington, D.C., 1972.

Gurnett, D.A., and L.A. Frank, A region of intense plasma wave turbulence on auroral field lines, J. Geophys. Res., 82, 1031, 1977.

Gurnett, D.A., Electromagnetic plasma wave emissions from the auroral field lines, J. Geomagnet. and Geoelectr., 30, 257, 1978.

Harel, M., R.A. Wolf, P.H. Reiff, R.W. Spiro, W.J. Burke, F.J. Rich, and M. Smiddy, Quantitative simulation of a magnetospheric substorm, 1. Model logic and overview, submitted to J. Geophys. Res., 1980a.

Harel, M., R.A. Wolf, R.W. Spiro, P.H. Reiff, C.-K. Chen, W.J. Burke, F.J. Rich, and M. Smiddy, Quantitative simulation of a magnetospheric substorm, 2. Comparison with observations, submitted to J. Geophys. Res., 1980b.

Hasegawa, A., Particle acceleration by MHD surface wave and formation of aurora, J. Geophys. Res., 81, 5083, 1976.

Hubbard, R.F., and G. Joyce, Simulation of auroral double layers, J. Geophys. Res., 84, 4297, 1979.

Hudson, M.K., and F.S. Mozer, Electrostatic shocks, double layers, and anomalous resistivity in the magnetosphere, Geophys. Res. Lett., 5, 131. 1978.

Hudson, M.K., R.L. Lysak, and F.S. Mozer, Magnetic field-aligned potential drops due to electrostatic ion cyclotron turbulence, Geophys. Res. Lett., 5, 143, 1978.

Hultqvist, B., H. Borg, W. Riedler, and P. Christopherson, Observations of magnetic field-aligned anisotropy for 1 and 6 keV positive ions in the upper ionosphere, Planet. Space Sci., 19, 279, 1971.

Hultqvist, B., On the interaction between the magnetosphere and the ionosphere, in Solar-Terrestrial Physics/Proc. of the International Symp., Leningrad, USSR, May 11-19, 1970, ed. by E.R. Dyer, pp. 176-198, D. Reidel, Dordrecht-Holland, 1972.

Hultqvist, B., The hot ion component of the magnetospheric plasma and some relations to the electron component — observations and physical implications, Space Sci. Rev., 23, 581, 1979.
Iijima, T., and T.A. Potemra, Large-scale characteristics of field-aligned currents associated with substorms, J. Geophys. Res., 81, 3999, 1976.
Iizuka, S., K. Saeki, N. Sato, and Y. Hatta, Buneman instability, Pierce instability, and double layer formation in a collisionless plasma, Phys. Rev. Lett., 43, 1404, 1979.
Ionson, J.A., R.S.B. Ong, and E.G. Fontheim, Anomalous resistivity of the auroral plasma in the topside ionosphere, Geophys. Res. Lett., 3, 549, 1976.
Jaggi, R.K., and R.A. Wolf, Self-consistent calculation of the motion of a sheet of ions in the magnetosphere, J. Geophys. Res., 78, 2842, 1973.
Joyce, G., and R.F. Hubbard, Numerical simulation of plasma double layers, J. Plasma Phys., 20, 391, 1978.
Kamide, Y., and S. Matsushita, Simulation studies of ionospheric electric fields and currents in relation to field-aligned currents, 1. Quiet periods, J. Geophys. Res., 84, 4083, 1979a.
Kamide, Y., and S. Matsushita, Simulation studies of ionospheric electric fields and currents in relation to field-aligned currents, 2. Substorms, J. Geophys. Res., 84, 4099, 1979b.
Kan, J.R., Energization of auroral electrons by electrostatic shock waves, J. Geophys. Res., 80, 2089, 1975.
Kan, J.R., L.C. Lee, and S.-I. Akasofu, Two-dimensional potential double layers and discrete auroras, J. Geophys. Res., 84, 4305, 1979.
Kan, J.R. and L.C. Lee, On the auroral double layer criterion, J. Geophys. Res., 85, 788, 1980a.
Kan, J.R. and L.C. Lee, Theory of imperfect magnetosphere-ionosphere coupling, Geophys. Res. Lett., 7, 633, 1980c.
Karlson, E.J., Streaming of plasma through a magnetic dipole field, Phys. Fluids, 6, 798, 1963.
Kindel, J.M., and C.F. Kennel, Topside current instabilities, J. Geophys. Res., 76, 3055, 1971.

Kintner, P.M., M.C. Kelley, R.D. Sharp, A.G. Ghielmetti, M. Temerin, C. Cattell, P.F. Mizera, and J.F. Fennell, Simultaneous observations of energetic (keV) upstreaming ions and electrostatic hydrogen cyclotron waves, J. Geophys. Res., 84, 7201, 1979.

Knorr, G., and C.K. Goertz, Existence and stability of strong potential double layers, Astrophys. Space Sci., 31, 209, 1974.

Langmuir, I., The interaction of electron and positive ions space charges in cathode sheaths, Phys. Rev., 33, 954, 1929.

Lee, L.C., and J.R. Kan, Nonlinear ion acoustic wave and soliton in a magnetized plasma, Phys. Fluids, (in press), 1980.

Lee, L.C., and J.R. Kan, Auroral double layers in Plasma Processes of Discrete Auroras, Geophysical Monograph Series, AGU, 1981.

Levine, J.S., D.B. Ilić, and F.W. Crawford, Laboratory observations of plasma double layers, J. Geomag. Geoelectr., 30, 461, 1978.

Levine, J.S., and F.W. Crawford, A fluid description of plasma double-layers, J. Plasma Phys., 23, 223, 1980.

Lin, C.S., and R.A. Hoffman, Characteristics of the inverted V event, J. Geophys. Res., 84, 1514, 1979.

Lyons, L.R., D.S. Evans, and R. Lundin, An observed relation between magnetic field aligned electric fields and downward electron energy fluxes in the vicinity of auroral forms, J. Geophys. Res., 84, 457, 1979.

Lyons, L.R., Generations of large-scale regions of auroral currents, electric potentials, and precipitation by the divergence of the convection electric field, J. Geophys. Res., 85, 17, 1980.

Maggs, J.E., and T.N. Davis, Measurements of the thickness of auroral structures, Planet. Space Sci., 16, 205, 1968.

Mallinckrodt, A.J., and C.W. Carlson, Relations between transverse electric fields and field-aligned currents, J. Geophys. Res., 83, 1426, 1978.

Mal'tsev, Yu. P., The effect of ionospheric conductivity on the convection system in the magnetosphere, Geomag. Aeron., 4, 128, 1974.

Mason, R.J., Computer simulation of ion-acoustic shocks, II. Slug and piston problems, Phys. Fluids, 15, 845, 1972.

Meng, C.-I., Electron precipitations and polar auroras, Space Sci. Rev., 22, 223, 1978.

Mizera, P.F., and Fennell, J.F., Signature of electric fields from high and low altitude particle distributions, Geophys. Res. Lett., 4, 311, 1977.

Miura, A., and T. Sato, Numerical simulation of global formation of auroral arcs, J. Geophys. Res., 85, 73, 1980.

Moiseev, S.S., and R.Z. Sagdeev, Collisionless shock waves in a plasma in a weak magnetic field, Plasma Phys., 5, 43. 1963.

Montgomery, D., and G. Joyce, Shock-like solutions of the electrostatic Vlasov equations, J. Plasma Phys., 3, 1, 1969.

Myra, J.R., and C.S. Liu, Nonlinear stabilization of the ion-beam-cyclotron instability, Phys. Rev. Lett., 43, 861, 1979.

Nisbet, J.S., M.J. Miller, and L. A. Carpenter, Currents and electric fields in the ionosphere due to field-aligned auroral currents, J. Geophys. Res., 83, 2647, 1978.

Nopper, R.W. Jr., and R.L. Carovillano, Polar equatorial coupling during magnetically active periods, Geophys. Res. Lett., 5, 699, 1978.

Nopper, R.W. Jr., and R.L. Carovillano, Ionospheric electric fields driven by field-aligned currents, in Quantitative Modeling of the Magnetospheric Processes, Geophys. Monogr. Soc., 21, ed. by W. P. Olson, p. 557, AGU, Washington, D.C., 1979.

Palmadesso, P.J., T.P. Coffey, S.L. Ossakow, and K. Papadopoulos, Topside ionosphere ion heating due to electrostatic ion cyclotron turbulence, Geophys. Res. Lett., 1, 105, 1974.

Papadopoulos, K., A review of anomalous resistivity for the ionosphere, Rev. Geophys. Space Phys., 15, 113, 1977.

Persson, H., Electric field along a magnetic line of force in a low-density plasma, Phys. Fluids, 6, 1756, 1963.

Persson, H., Electric field parallel to the magnetic field in a low-density plasma, Phys. Fluids, 9, 1090, 1966.

Ponyavin, D.I., M.I. Pudovkin, and S.S. Sazhin, Self-consistent field-aligned electric field in the earth's magnetosphere, Geomag. and Aeron., 17, 323, 1977.

Quon, B.M., and A.Y. Wong, Formation of potential double layers in plasmas, Phys. Rev. Lett., 37, 1393, 1976.

Rostoker, G., and R. Boström, A mechanism for driving the gross Birkeland current configuration in the auroral oval, J. Geophys. Res., 81, 235, 1976.

Sakanaka, P.H., C.K. Chu, and T.C. Marshall, Formation of ion-acoustic collisionless shocks, Phys. Fluids, 14, 611, 1971.

Sato, T., A theory of quiet auroral arcs, J. Geophys. Res., 83, 1042, 1978.

Sato, T., and H. Okuda, Ion acoustic double layer, Phys. Rev. Lett., 44, 740, 1980.

Sharp, R.D., R.G. Johnson, and E.G. Shelley, Energetic particle measurements from within ionospheric structures responsible for auroral acceleration processes, J. Geophys. Res., 84, 480, 1979.

Singh, N., and H. Thiemann, Some features of inverted V events as seen from simulated double layers, Geophys. Res. Lett., (accepted), 1980.

Sonnerup, B.U.Ö., Theory of the low-latitude boundary layer, J. Geophys. Res., 85, 2017, 1980.

Southwood, D.J., and R.A. Wolf, An assessment of the role of precipitation in magnetospheric convection, J. Geophys. Res., 83, 5227, 1978.

Stenzel, R.L., M. Ooyama, and Y. Nakamura, Potential double layers formed by ion beam reflection in magnetized plasmas, in Physics of Auroral Arc Formation, AGU Publication, 1981.

Swift, D.W., On the formation of auroral arcs and the acceleration of auroral electrons, J. Geophys. Res., 80, 2096, 1975.

Swift, D.W., An equipotential model of auroral arcs, 2. Numerical solutions, J. Geophys. Res., 81, 3935, 1976.

Swift, D.W., An equipotential model for auroral arcs: The theory of two-dimensional laminar electrostatic shocks, J. Geophys. Res., 84, 6427, 1979.

Temerin, M., The polarization, frequency, and wavelengths of high-altitude turbulence, J. Geophys. Res., 83, 2609, 1978.

Temerin, M., M. Woldorff, and F.S. Mozer, Nonlinear steepening of the electrostatic ion cyclotron wave, Phys. Rev. Lett., 43, 1041, 1979.

Tidman, D.A. and N.A. Krall, Shock Waves in Collisionless Plasmas, John Wiley and Sons, Inc., 1971.

Torvén, S. and M. Babic, Current chopping space charge layers in a low pressure arc plasma, Proc. 12th Int. Conf. on Phenomena in Ionized Gases, Eindhoven, Netherlands, Aug. 18-22, 124, North-Holland Publ. Co., 1975.

Volland, H., Models of global electric fields within the magnetosphere, Ann. Geophys., 31, 154, 1975.

Vasyliunas, V.M., Mathematical models of magnetospheric convection and its coupling to the ionosphere, in Particles and Fields in the Magnetosphere, ed. by B. McCormac, p. 60, D. Reidel, Dordrecht-Holland, 1970.

Vasyliunas, V.M., The interrelationship of magnetospheric processes, in Earth's Magnetospheric Processes, ed. by Mccormac, p. 29, D. Reidel, Dordrecht-Holland, 1972.

Wagner, J.S., T. Tajima, J.R. Kan, J.N. Leboeuf, S.-I. Akasofu, and J.M. Dawson, V-potential double layers and the formation of auroral arcs, Phys. Rev. Lett., 45, 803, 1980.

Whipple, E.C., The signature of parallel electric fields in a collisionless plasma, J. Geophys. Res., 82, 1525, 1977.

Wolf, R.A., Effects of ionospheric conductivity on convective flow of plasma in the magnetosphere, J. Geophys. Res., 75, 4677, 1970.

Wolf, R.A., Calculations of magnetospheric electric fields, in Magnetospheric Physics, ed. by B. McCormac, p. 167, D. Reidel, Dordrecht-Holland, 1974.

Yasuhara, F. and S.-I. Akasofu, Field-aligned currents and ionospheric electric fields, J. Geophys. Res., 82, 1279, 1977.

Figure Captions

Figure 1. Schematic illustration of the S-shaped and V-shaped equipotential structures (dashed curved) along converging magnetic field lines.

Figure 2. Schematic illustration of particle trajectories of (1) precipitating magnetospheric electrons; (2) magnetospheric ions; (3) ionospheric ions; (4) ionospheric electrons; and (5) trapped and backscattered electrons.

Figure 3. A flow chart for the imperfect magnetosphere-ionosphere coupling.

Figure 4. A schematic illustration of the imperfect magnetosphere-ionosphere coupling along a meridianal plane (the x axis is positive northward) in the evening sector.

Figure 5. Comparison of the potential ϕ, the average velocity $\langle V \rangle$ and the average kinetic energy gain K between the double layer and the electrostatic shock.

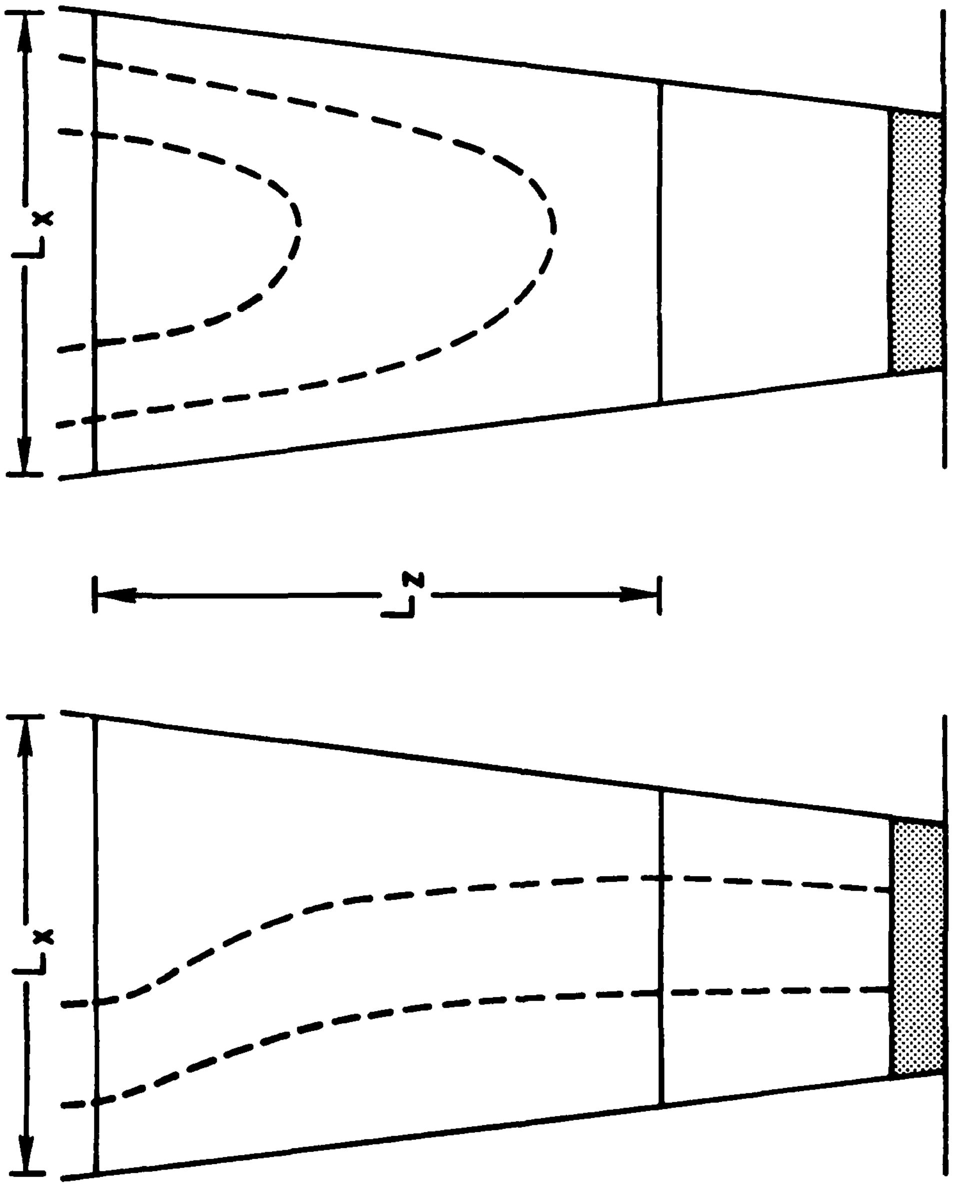
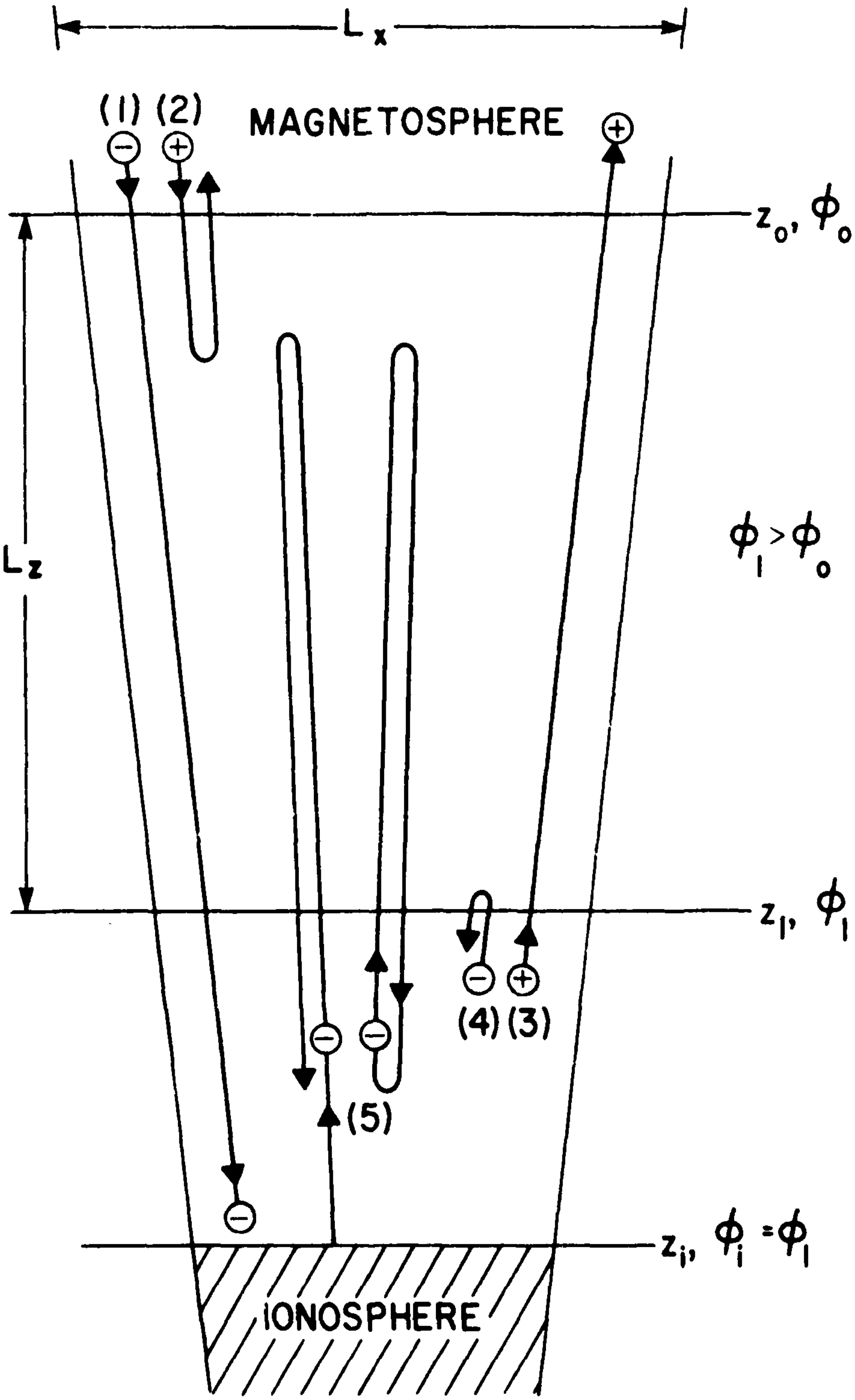


Figure 1



L x
(1) (2)
MAGNETOSPHERE
z o, φ o
L z
φ 1 > φ o
z 1, φ 1
(4) (3)
(5)
z i, φ i = φ 1
IONOSPHERE

Figure 2

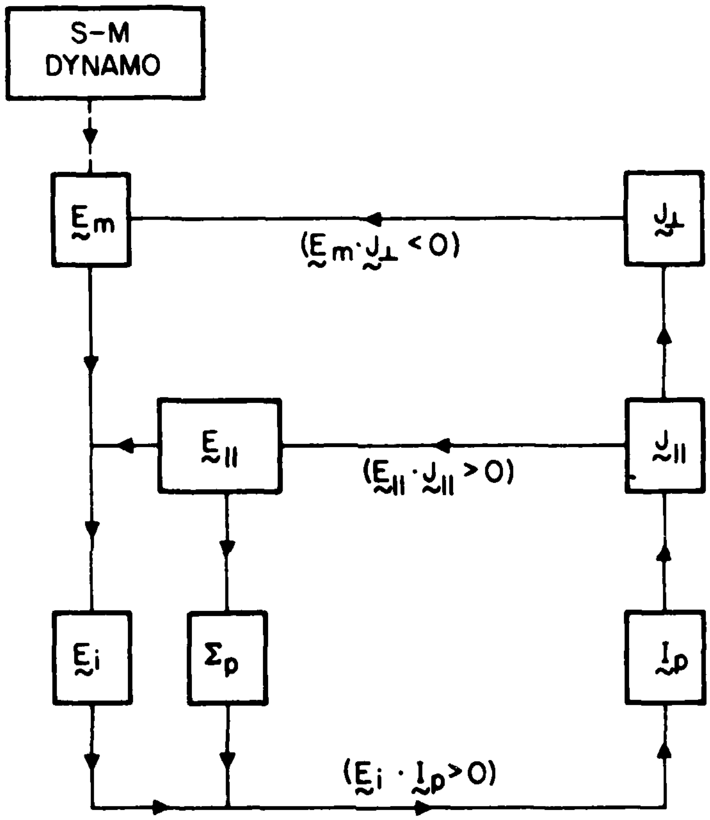

S-M DYNAMO
$\underset{\sim}{E}_m$
$\underset{\sim}{J}_\perp$
$(\underset{\sim}{E}_m \cdot \underset{\sim}{J}_\perp < 0)$
$\underset{\sim}{E}_{\parallel}$
$\underset{\sim}{J}_{\parallel}$
$(\underset{\sim}{E}_{\parallel} \cdot \underset{\sim}{J}_{\parallel} > 0)$
$\underset{\sim}{E}_i$
Σ_p
$\underset{\sim}{I}_p$
$(\underset{\sim}{E}_i \cdot \underset{\sim}{I}_p > 0)$

Figure 3

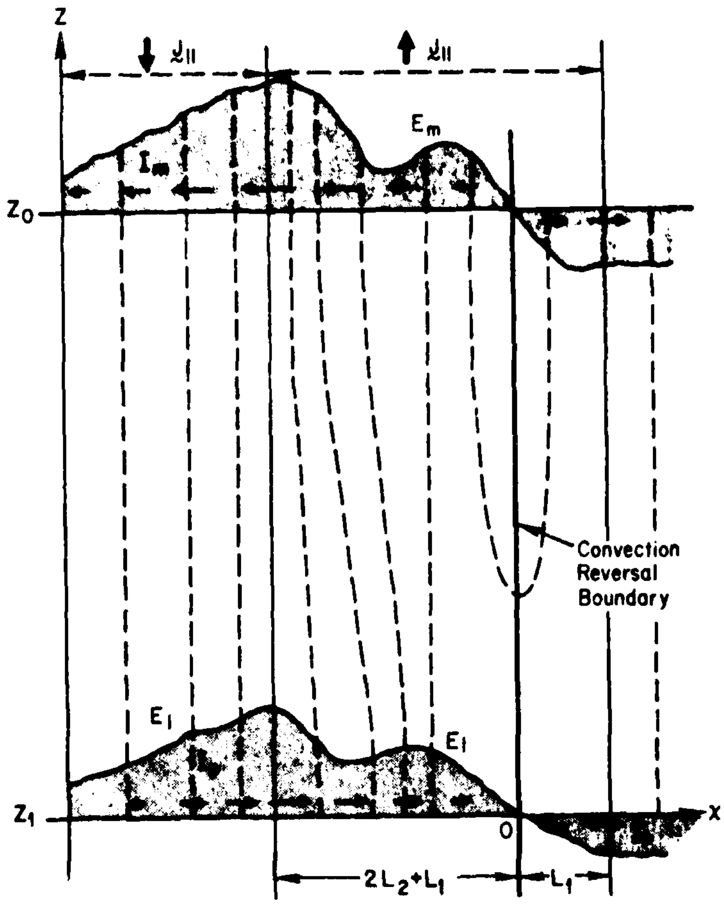
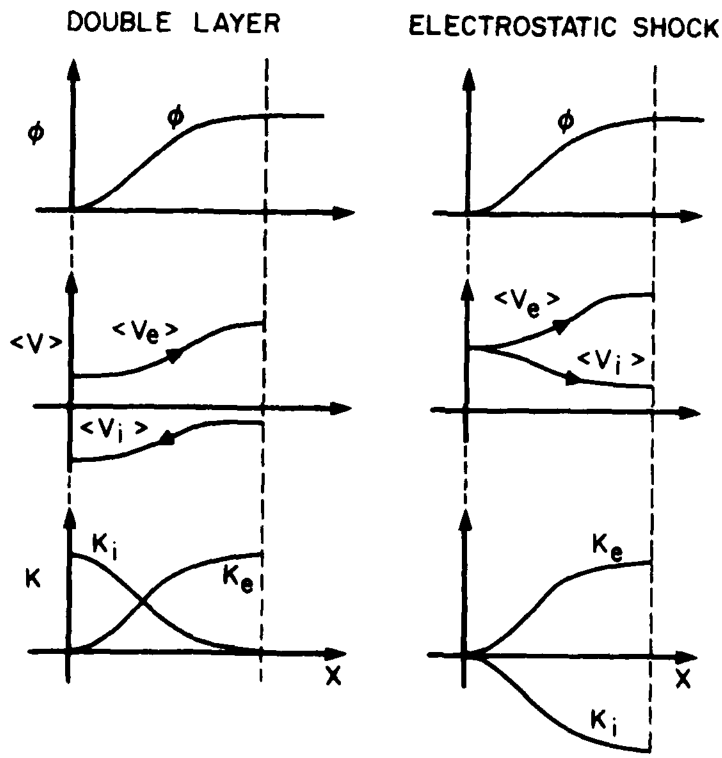

Z
$\downarrow \mathcal{J}_{\parallel}$
$\uparrow \mathcal{J}_{\parallel}$
E_m
I_m
Z_0
Convection
Reversal
Boundary
E_1
E_1
Z_1
0
X
$2L_2+L_1$
L_1

Figure 4


DOUBLE LAYER
ELECTROSTATIC SHOCK
φ
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K
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Ke
Ki
X
X

Figure 5